LCA Case Studies

Life Cycle Assessment of the Selective Catalytic Reduction Process for Power Plants

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Abstract. The overall reduction of the environmental impact by the use of selective catalytic reduction (SCR) of nitrogen oxide emissions in power plants was determined by strict application of ISO 14040 and ISO/DIS 14041. Special emphasis was placed on the implementation of the total product life cycle (PLC) of ammonium molybdate as a key input material. The environmental impact was generated by application of the life cycle assessment (LCA) concept of "ecoscarcity" and integrated in the life cycle inventory analysis (LCI) of SCR systems. The LCI was used to generate the life cycle impact assessment (LCIA) by use of different quantitative valuation methods. Under consideration of the overall LCIA results and the environmental protection costs of the SCR variants, the Ecological Effectiveness of the SCR alternatives was determined. The results enable plausible conclusions with regard to the ecological advantages of the use of deNOx catalysts in the SCR used in hard-coal fired power plants.

Keywords: Coal combustion plants; $deNO_x$ catalysts; Life Cycle Assessment; life cycle inventory analysis; nitrogen oxides; selective catalytic reduction

1 Introduction (→ *Fig. 1*)

Following the implementation of primary measures in hard coal-fired power plants, the NO_x values in the flue gas are typically 1,000 mg/m³ (as NO_2, in standard condition, dry, reference O_2) for plants with slag tap firing, or 800 mg/m³ (as NO_2, in standard condition, dry, reference O_2) for plants with dry bottom firing (P_{el} = 200 MW, electric power reference designs). The implementation of secondary-emission control measures is absolutely necessary to reduce emissions in the flue gases of large combustion facilities below the limit of 200 mg/m³ (as NO_2, in standard condition, dry, reference O_2) determined by the conference of environmental ministers of the F.R.G. from 5th April 1984 [1]. This is achieved nearly exclusively with SCR (→ *Fig. 1, p. 330*). The primary reactions in the SCR of NO_x proceed as follows with the addition of ammonia (NH_3) as the reducing agent [2]:

$$4\,NO + 4\,NH_3 + O_2 \rightarrow 4\,N_2\uparrow + 6\,H_2O \qquad (1)$$

$$6\,NO_2 + 8\,NH_3 \rightarrow 7\,N_2\uparrow + 12\,H_2O \qquad (2)$$

Without the use of catalysts, the reactions given above do not proceed until the temperature exceeds 800 - 900°C. Increasing the temperature to above 1,050 - 1,200°C results in oxidation of the NH_3 to NO. The reaction rate is very low below 800 - 900°C. The effectiveness of the catalysts is tracked by regular sampling during operation and measurement of their catalytic activity. Plate-type catalysts are used in the temperature range from 300 - 450°C. These consist of an expanded stainless steel mesh which is coated with the catalytically active material [primary material (TiO_2), active component (V_2O_5) and additives (WO_3 and/or MoO_3)]. The specific surface area is typically 250 - 500 m²/m³. Honeycomb catalysts are implemented in power plants at temperatures of approx. 300 - 450°C. In contrast to otherwise typical supported catalysts, honeycomb-type SCR catalysts are made up of extruded blocks consisting exclusively of the catalytically active material. These have a specific surface area of 400 - 1,000 m²/m³ (up to 1,900 m²/m³ for special applications). The purpose of this manuscript is to extend the LCA of SCR systems edited in [3] by strict application of the international Standards ISO 14040 [4] and ISO/DIS 14041 [5], inclusion of the manufacturing processes for the remaining input materials for the manufacture of $deNO_x$ catalysts and use of different quantitative valuation methods.

2 Method

2.1 Concept of "ecoscarcity" (→ *Fig. 2*)

This concept (→ *Fig.* 2) was determined to be suitable for performing this analysis. The assumptions of this method are explained briefly below [6]:

- *Direct impacts on the environment* by a process result from an actual direct exchange with nature.
- *Indirect impacts on the environment* are represented by the influences on the environment by other processes.
- *Primary impacts on environment* are those which take place in the form of acquisitions from suppliers or deliveries to disposal facilities (e.g. waste water discharge in sewage system).
- *Secondary impacts on the environment* arise at the disposal facility by the transformation of primary impacts on the environment or at the supplier level by the provision of energy and materials.

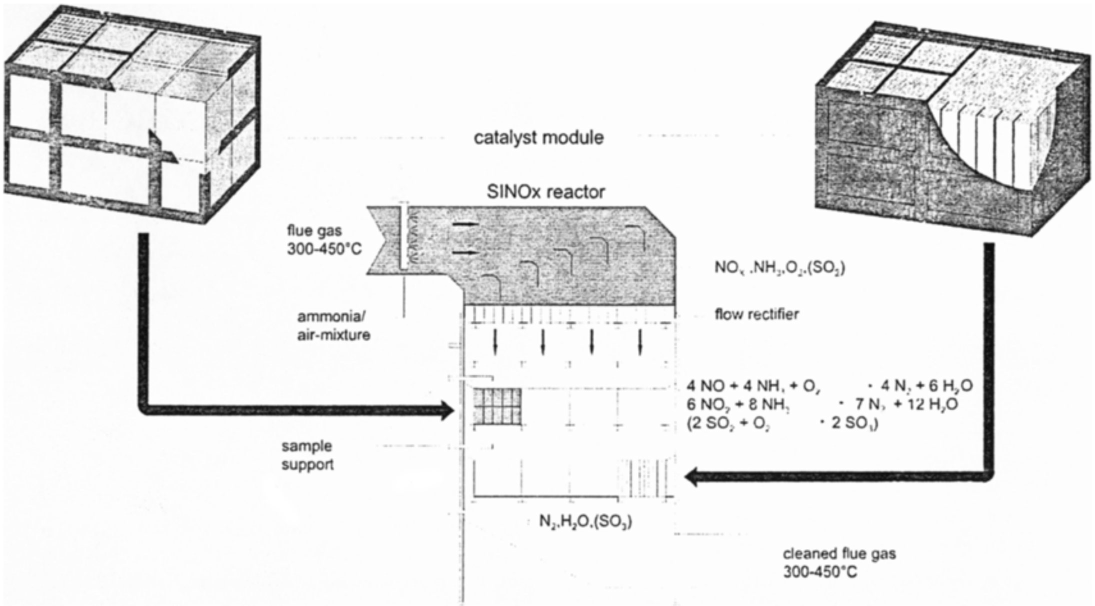

Fig. 1: Application of deNO_x catalysts in SCR [2]

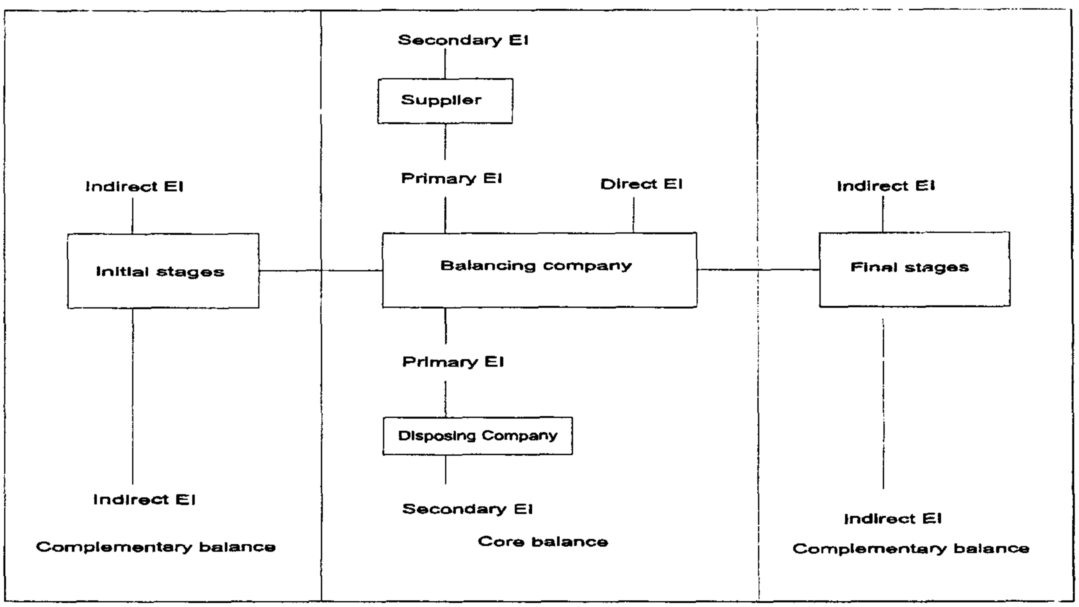

Fig. 2: Core and complementary balance [6]

2.2 Process sequence, goal definition, scoping and LCI (→ *Fig. 3*)

The following methods were used as tools to establish a detailed LCI (→ *Table 1, Annex, p. 338*) according to the concept of "ecoscarcity". The influences on the environment were strictly separated into direct and secondary influences.

- Process sequence analysis method,
- Process input-output analysis method and
- Method of cumulated energy demand [7].

Detailed data in a form usable in LCA was determined and used to investigate the PLC of deNO_x catalysts, with the primary goal being a critical evaluation of the ecological justifiability of SCR and a presentation of the ecologically critical process steps. This analysis comprises the following main points (→ *Fig. 3*):

- Generation of the LCA for the production process of plate and honeycomb-type deNO_x catalysts (manufacturing process, our own inquiry),
- Expansion of LCA for deNO_x catalysts to include suppliers of input materials (data from the suppliers of input materials),
- Expansion of LCA for deNO_x catalysts to include the implementation in hard-coal fired power plants (reference design with typical parameters on an average value, data from reports of an electrical power plant contractor) and

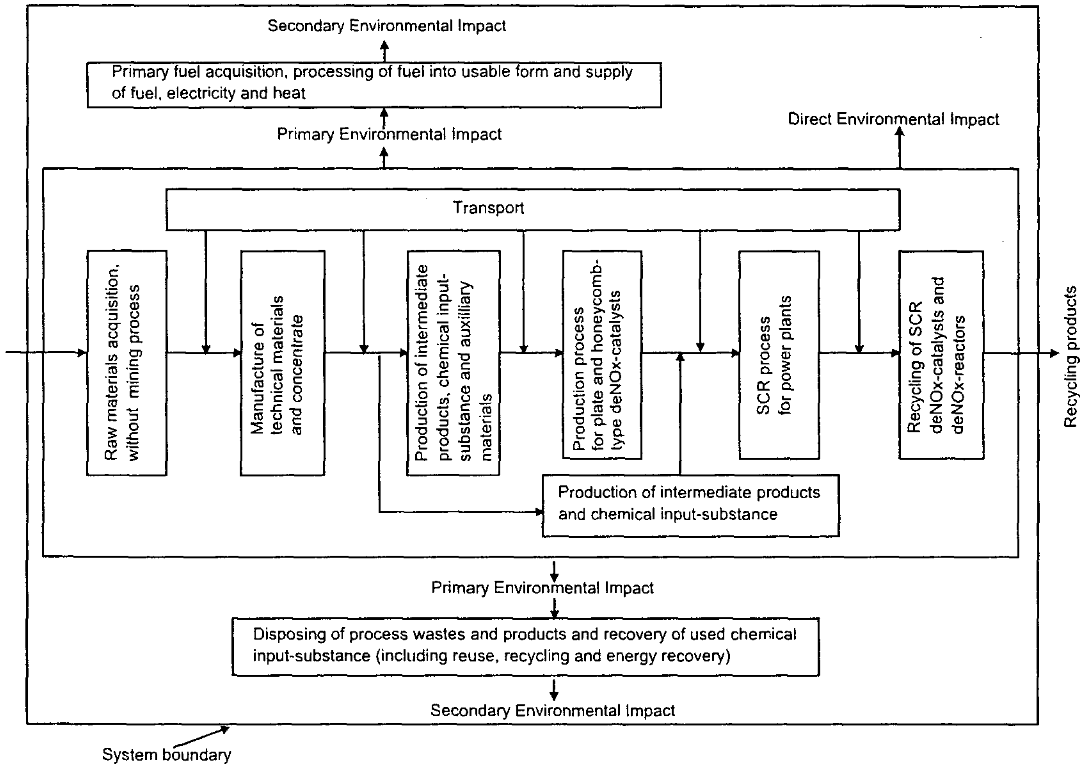

Fig. 3: System scope for the LCA of the SCR process

- Expansion of LCA for deNO$_x$ catalysts to include processing of spent catalysts following service in power plants (own inquiry of the data based on the design of the spent catalysts processing plant).

The process sequences were divided into suitable subprocesses for the LCA of the manufacturing process for deNO$_x$ catalysts. The materials used were allocated to the various process steps based on their material composition. Each process step of the manufacturing process and treatment of environmental burden were described and flow diagrams for the process sequences were obtained [8]. A wide range of manufacturing and measurement logs as well as basic physical and chemical laws were used to determine the energy and mass flows for each process sequence. Data were used from energy, water, waste water, emission measurements and waste reports, together with information on the type of disposal or recycling. As far as possible, real consumption data were used for the inventory analysis from the downstream environmental protection measures. The technical and numerical relationships between each manufacturing and environmental subprocess were determined as proportionality factors and incorporated in a computational model. Arrangement of the mass flows determined in a inventory analysis such as a hierarchical input-output balance (e.g. by raw, auxiliary, operating materials, etc.) and the inclusion of plant operating data and specifications enabled extension of the actual mass flows by auxiliary or operating material flows which are low volume or which cannot be directly influenced. The overall impact of the energy consumption on the environment was calculated by determining the cumulated energy demand for each energy source [7] and accounting for measured emissions and average emission values for the production process sequence. Extension of the LCA to the suppliers of input materials was limited to product input materials and the most important input materials by weight, energy and environmental relevance for manufacturing the deNO$_x$ catalysts. The extension included the performance of each corresponding manufacturing process and the associated process steps relevant to the environment. The core balances for each of the input materials listed above were generated, analogous to those for catalyst manufacture, in accordance with the "ecoscarcity" LCA concept. If the advantage of a process currently in use was not clearly recognizable, the effects of various production methods in the manufacture of an input material on the ecologic balance of the manufacturing process for deNO$_x$ catalysts were determined as a sensitivity analysis by generating the LCA for the alternative processes which could be considered. This investigation is intended to summarize and present the effects on the environment from the manufacture of:

- Steel (80% from the basic oxygen process and 20% from the electric arc process),
- Ammonia (steam-reforming process with natural gas as a raw material),
- Sulfuric acid (double catalytic contact process),
- Titanium oxide powder (TiO_2 from sulfate process with 80% magnesium oxychloride slag and 20% ilmenite, without ore recovery),
- Ammonium vanadate from oil combustion residues and
- Ammonium molybdate (hydrometallurgical manufacture and technical MoO_3 manufacture).

No complete inclusion of all environmental impacts was attempted, as this would only have been possible at unjustifiable expense due to the complexity of the manufacturing processes and the global distribution of the suppliers of raw materials. Special emphasis was therefore placed on the plausibility of the results obtained. Data collected for the LCI of each process sequence were examined by the respective manufacturers regarding accuraccy, precision, representativeness and completeness. Recommendations of the manufacturers were pursued consequently. The following four variants (→ *Table 2, Annex, p. 338*) were considered for honeycomb and plate-type deNO_x catalysts in a typical hard-coal power plant with P_{el} = 200 MW (reference design electrical power with typical flue gas parameters and NO_x reduction rates) for ecological balancing of catalyst use in power plants:

- V_1: High-dust system for slag tap firing (hard coal), 1,000 m^3 plate type 1,
- V_2: High-dust system for dry firing (hard coal), 1,000 m^3 plate type 2,
- V_3: High-dust system for dry firing (hard coal), 1,000 m^3 honeycomb,
- V_4: Low-dust system downstream of FGD (hard coal), 1,000 m^3 honeycomb

The following key figures were considered for the evaluation of variant V_4:
Reheating of the cold flue gases from T = 45°C at the FGD outlet (for hard coal firing with Ruhr coal) to the operating temperature of 300°C for deNO_x catalyst (V_4) proceeds in three stages:

- Flue gas preheating to 90°C by regenerative gas heater with flue gases upstream of FGD inlet (T = 120°C),
- Flue gas preheating to 285°C by regenerative gas heater with flue gases downstream of deNO_x reactor (T = 300°C) and
- Heating to 300°C with natural gas burner.

The different variants were compared based on the overall PLC of 1,000 m^3 of deNO_x catalyst as the core component of the SCR process. Starting with typical reference designs for the different variants (→ *Table 2, Annex, p. 338*), the service life of 1,000 m^3 of deNO_x catalyst in the SCR process was determined for each of the above variants (→ *Table 3, Annex, p. 339*). Based on the determined service life of 1,000 m^3 deNO_x catalyst in the electrical power plants, the yearly operating time of the electrical power plants and the technical service life of the electrical power plants, the number of deNO_x reactors for each of the above variants was calculated regarding the total amount of 1,000 m^3 of catalyst par variant. The resulting direct influences on the environment are given in Table 3. The secondary influences of the SCR process on the environment include the processes for steel and NH_3 production, for the construction of the deNO_x reactor and the actual SCR of NO_x, the energy supply process sequence (natural gas) for the low-dust variant and the process sequence for transport of the deNO_x catalysts from manufacturing to where they are used in the power plants. Two different disposal/recycling paths were considered to account for impact on the environment in the processing of spent deNO_x catalysts following use in power plants:

- Recycling of the spent honeycomb-type deNO_x catalysts and the steel as well as
- Recycling of the plate-type deNO_x catalysts as an additive in steel production.

The entire transport process sequence and the process sequence for power supply in the Federal German interconnected power system were accounted for in representing the influences on the environment.

2.3 Life Cycle Impact Assessment

The LCI was used to generate the LCIA with the following quantitative valuation methods:

- The "ecoscarcity"-approach, Swiss data from [6].
- The Tellus-system, data mainly from Tellus Intitute, Boston, see [9].
- The EPS-system (Environmental Priority Strategies in product design), data mainly from [9].
- The "effect-category", short time, data from [9].
- The "effect-category", long time, data from [9].
- The "Concept of Quality target Relations" (CQR), data from [9],
- The "ecoscarcity"-approach, Norwegian data from [9],
- The "ecoscarcity"-approach, Swedish data from [9].

The significance of the "ecoscarcity" concept is that, to a certain extent, an inadmissible deterioration of the condition of an environmental resource can be prevented only by a restriction of the anthropogenic impact on this resource. The authors of the concept base the formulation of the improvement assessment on the terms of "critical flow" (Fc) and "actual flow" (F) [6]. The first term is a mass flow based on a specific area which does not have any undesired deteriorating effect on the condition of the environmental resource under consideration. The second term represents the actual mass flows. Both terms serve as the basis for the determination of the ecological factor and the ecological burden points (EBP):

Ecological factor = 1/Fc x F/F (3)

EBP = influence on environment x ecological factor (4)

The Tellus-system is a valuation method based on control costs of a number of pollutants used to establish prices in U.S. $/kg for some criteria air pollutants [9]. In the EPS-system, five safe guard objects (biodiversity, production, human health, resources and aesthetic) are valued according to the willingness to pay to restore them to their normal status. Emissions, use of resources and other human activities are then valued according to their estimated contribution to the changes in the safe guard objects. The environmental values are expressed as Environmental Load Units (ELU) per emission unit or other human activities, e.g. 2.17 10^{-1} ELU/kg NO_x. The value of one ELU is approximately one European Currency Unit (ECU). The results of both, Tellus and EPS-systems, provide an economic valuation of the environmental impacts [9]. The "effect category" method for short and long time is based on a quantitative characterization used for positioning different options on an diagram with environmental yield on one axis and the economic

impact on the other axis. The scores for the different impact categories are normalized by relating the scores to the total score of that category in Sweden, thus resulting in an environmental profile. The different effect categories are then weighted against each other in two ways. For the short time method the weighting is based on Swedish political goals. In the long time method the weighting is based on assumed critical loads for the different categories. Based on these results, environmental weighting factors are calculated [9]. The "Concept of Quality target Relations" is based on different types of quality standards for air, water, and soil. The used quality standards are recalculated to mg/mol of the environmental medium and normalized by setting the valuation weighting factor for CO_2 to one. The environmental weighting factors are expressed as Environmental Pollution Source Units (EPSU) per kg emission [10].

The contribution to the bulk environmental burden impact from the in or output j, BB_j is calculated as the product of the amount or mass of the bulk burden on environment of the in or output of j (→ *Table 1, Annex, p. 338*), BBE_j, and the valuation weighting factor of the above mentioned valuation methods [9], V_j according to the equation (5).

$$BB_j = BBE_j * V_j \tag{5}$$

The goal of these methods is to sum up the influences on the environment starting with the bulk environmental burden impact, BB from the in or output, BB_j (equation (6)), enabling a comparison between various types of influences on the environment [9].

$$BB = \sum_{j=1}^{n}\left(BB_j\right) \tag{6}$$

The number of the bulk environmental burden impact BB is decisive for the evaluation. The higher the number of the bulk environmental burden impact results (equation 6), the more negatively the impact on the environment which arises is categorized. The bulk ecological relief (BR) of the LCIA for an environmental product such as $deNO_x$ catalysts in SCR systems can be generated as the product of the amount or mass of the bulk reduction of load on the environment of one specific or more in or output of j (→ *Table 1, Annex, p. 338*), $BRLE_j$, and the valuation weighting factor of the above mentioned valuation methods for these in or outputs, V_j according to the equation (7).

$$BR = \sum_{j=1}^{n}\left(BR_j\right) = \sum_{j=1}^{n}\left(BRLE_j \bullet V_j\right) \tag{7}$$

The overall ecological relief of the LCIA (R) for an environmental product can be calculated with the equation (8).

$$R = (BR - BB) = \sum_{j=1}^{n}\left(BR_j - BB_j\right) \tag{8}$$

The LCIA results given in **Table 6** (→ *Annex, p. 339*) were obtained for the PLC of SCR systems with $deNO_x$ catalysts. The determination of the Ecological Effectiveness (EE) of the process under consideration of the LCIA result (equation 8) and the environmental protection costs (EPC) of the process for comparison of various alternatives and techniques for reducing the load on the environment are defined in equation (9):

$$EE = \frac{R}{EPC} \quad \textit{[overall ecological relief units/U.S. \$]} \tag{9}$$

The ecological effectiveness (equation 9) point out the overall reduction of load on the environment during the overall life cycle for an environmental protection product, process or technology in relation to the environmental protection costs for this environmental protection product, process or technology. The higher the number of the ecological effectiveness results (equation 9), the better the impact on the environment which this environmental protection product, process or technology is categorized. The results from **Table 6** (→ *Annex, p. 339*) (overall ecological relief) and **Table 3** (→ *Annex, p. 339*) (environmental protection costs) were substituted into equation 9 to yield the results summarized in **Table 7** (→ *Annex, p. 339*) for the ecological effectiveness of SCR for the variants investigated.

3 Results, Discussion and Future Outlook

(→ *Fig. 4-9*)

The final results from **Table 7** (→ *Annex, p. 339*) and **Figure 4** confirm, according to all life cycle impact valuation methods used in this investigation, the following conclusions:

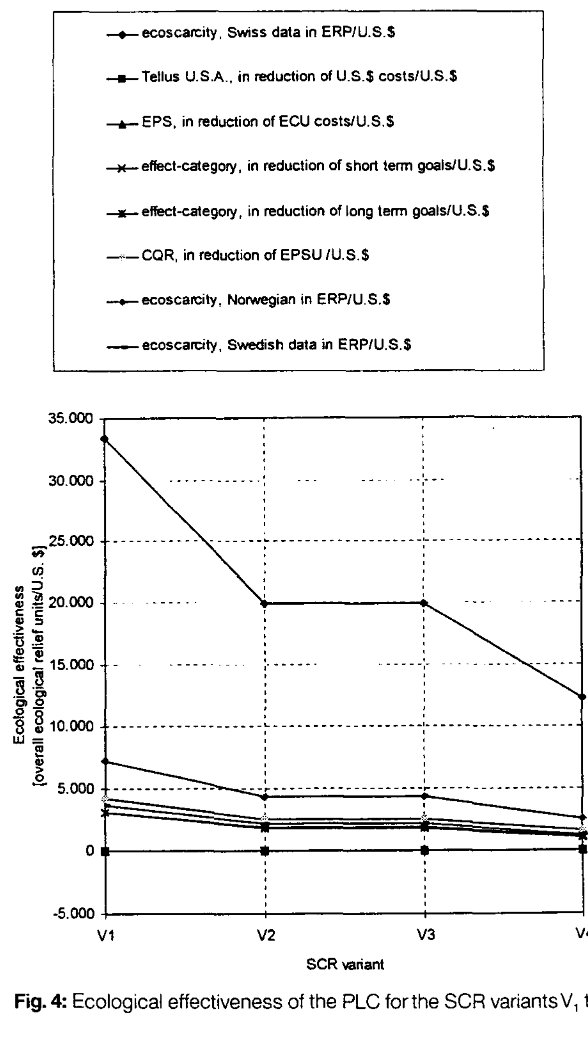

Fig. 4: Ecological effectiveness of the PLC for the SCR variants V_1 to V_4

1. The equipment of the existing plants with slag tap firing and high NO_x emissions have resulted in the best ecological relief.
2. More measures have been taken for cleaning the raw exhaust gas (form V_1 to V_4) before the application of SCR, the lower figures are the result of the ecological effectiveness of the SCR process.
3. The inclusion of the manufacturing processes for the remaining input materials for the manufacture of $deNO_x$ catalysts such as technical MoO_3 and for the generation of the LCIA of the high-dust SCR systems analyzed cannot cast any doubt on the clearly positive LCA results obtained in this and previous works.
4. The conclusion concerning the ecological effectiveness of SCR does not depend on the valuation method. Table 7 (→ *Annex, p. 339*) and Figure 4 show a clear trend of V_1 with higher and V_4 with lower ecological effectiveness.

The contribution of the product life cycle stages to the bulk environmental burden impact from the SCR variants V_1 to V_4 are shown in **Figure** 5 to 9. These final results confirm, according to all life cycle valuation methods used in this investigation, the following conclusions:

1. The highest contribution to the bulk environmental burden impact results during the application stage of the SCR process in power plants. The most important contribution of this result is given for the SCR variants V_1 to V_3 by the output of NH_3 slip during the SCR process in power plants and during the manufacturing process of the reduction agent. For the SCR variant V_4, the result is even clearer because of the additional and large contribution of the high energy consumption during the reheating of the cold flue gases to the operating temperature of 300°C for the deNOx catalysts.
2. The contribution of the recycling stage of the deNOx catalysts and deNOx reactors to the bulk environmental burden impact result is only marginal.
3. The contribution of the manufacturing process of technical materials, concentrate, intermediate products, chemical input-substance and ancillary materials to the bulk environmental burden impact result is for the SCR variants V_2 to V_4, according to all life cycle impact valuation methods, higher than the contribution of the production process for deNOx catalysts. Decisive for this result is the manufacturing process of TiO_2 for the honeycomb type deNOx catalysts. For plate type deNOx catalysts, the manufacturing process of TiO_2 and the production process of steel is significant.
4. For the SCR variant V_1 it is not possible to get a similar result for this comparison. The reason lies in the different valuations according to all life cycle impact valuation methods used for the disposing of hazardous waste to underground landfill.

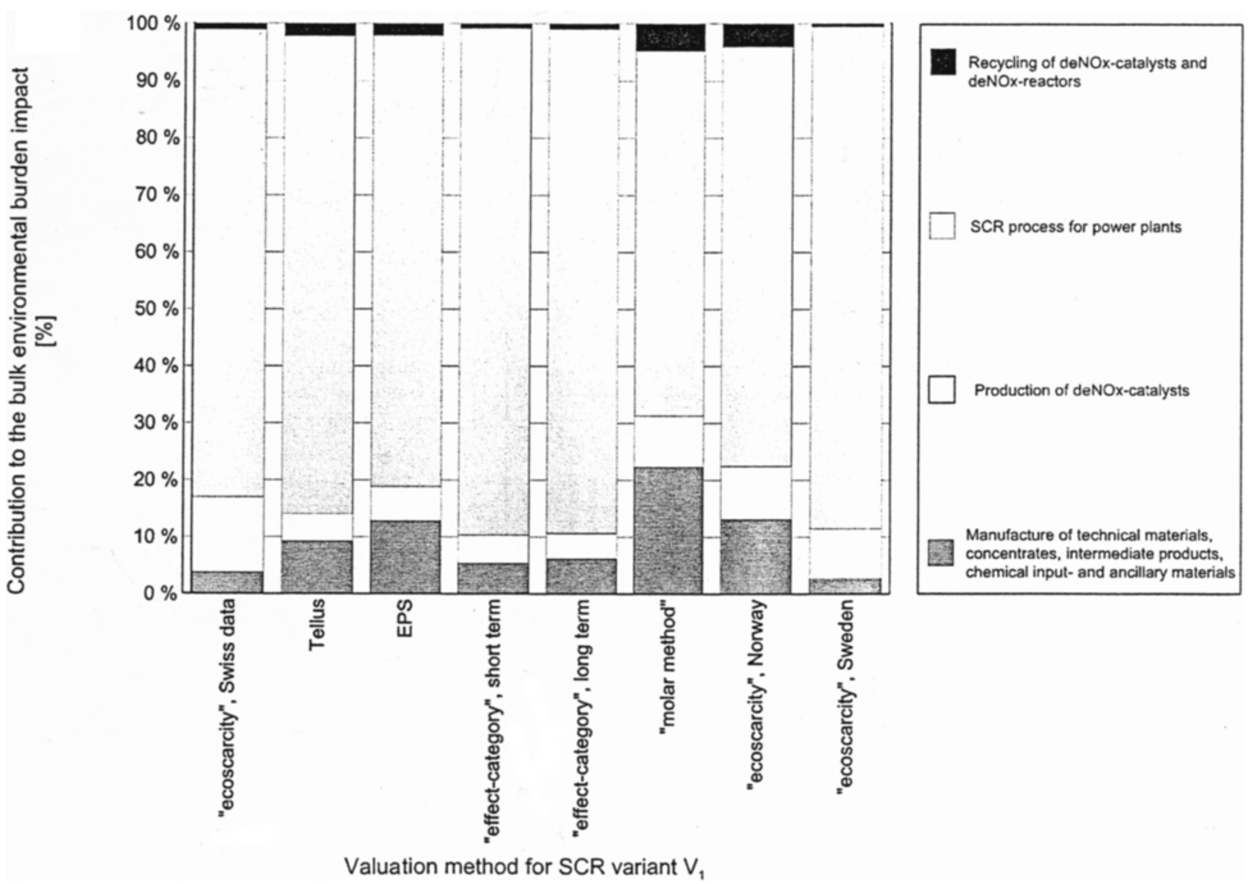

Fig. 5: Contribution from the PLC stages to the bulk environmental burden impact for the SCR variant V_1

5. **Figure** 9 shows the most important environmental pollutant emissions for SCR variant V_4 and its contribution to the bulk environmental burden impact according to all product life cycle valuation methods used. The contribution of these pollutant emissions to the bulk environmental burden impact depend on the valuation method used. The most important environmental burden results from the reheating of the cold flue gases to the operating temperature of the deNOx catalysts, the bulk emission of NO_x (as NO_2), the total emissions of NH_3, SO_2, CO_2, equivalent CO_2, CH_4 and NMVOC.

The ecological effectiveness results obtained are confined by the implementation variants analyzed. These results do not enable a conclusion about the ecological effectiveness of different technologies concerning power generation. This investigation has lead to the following conclusions for the ecological and cost optimization of SCR:

- The specific cumulated energy demand in MJ/kg NO_x (→ *Table 4* and *5, Annex, p. 339*) and the NO_x reduction costs of SCR (→ *Table 3, Annex, p. 339*) are on the average higher for the use of honeycomb-type $deNO_x$ catalysts than for plate-type catalysts, even under consideration of the price decrease for both types of catalyst since 1987. This is not compensated by the consideration of slightly higher specific reduction rates for the honeycomb-type catalyst over the plate-type catalyst (in kg NO_x/m^3 catalyst), due to differences in the specific surface area. However, this result is heavily influenced by the assumed 50% fraction of honeycomb-type catalyst in a low-dust configuration downstream of the FGD.
- As a consequence, further ecological and cost optimization of SCR can be achieved by increased implementation of $deNO_x$ catalysts for NO_x reduction in power plants in a high-dust configuration. This results in additional advantages for plate-type $deNO_x$ catalysts.

The above conclusions result from the specified conditions, including the data on the specific costs of SCR for the various implementation variants. An unrestricted transfer of the results to specific individual applications is therefore not possible. The specific NO_x reduction costs factor particularly heavily in each variant for the SCR system in the power plant. High influence results from the NO_x reduction rate in the SCR plant and the specific influence from exhaust gas conditions on the $deNO_x$ catalyst service life, e.g. by catalyst deterioration. For this reason, it is recommended that particular emphasis be placed on a detailed representation of the LCI in performing ecological balances, as the discussion is particularly subject to disagreement on the problem of evaluation. Existing LCI therefore enable rapid reanalysis if required.

In the following, studies the authors will investigate the LCA of the SCR process for other application variants, such as gas turbines for power plants, diesel motors for seagoing ships, inland waterway vessel, trucks, railway locomotives, railway cars, and gas motors for CO_2 fertilization in greenhouses.

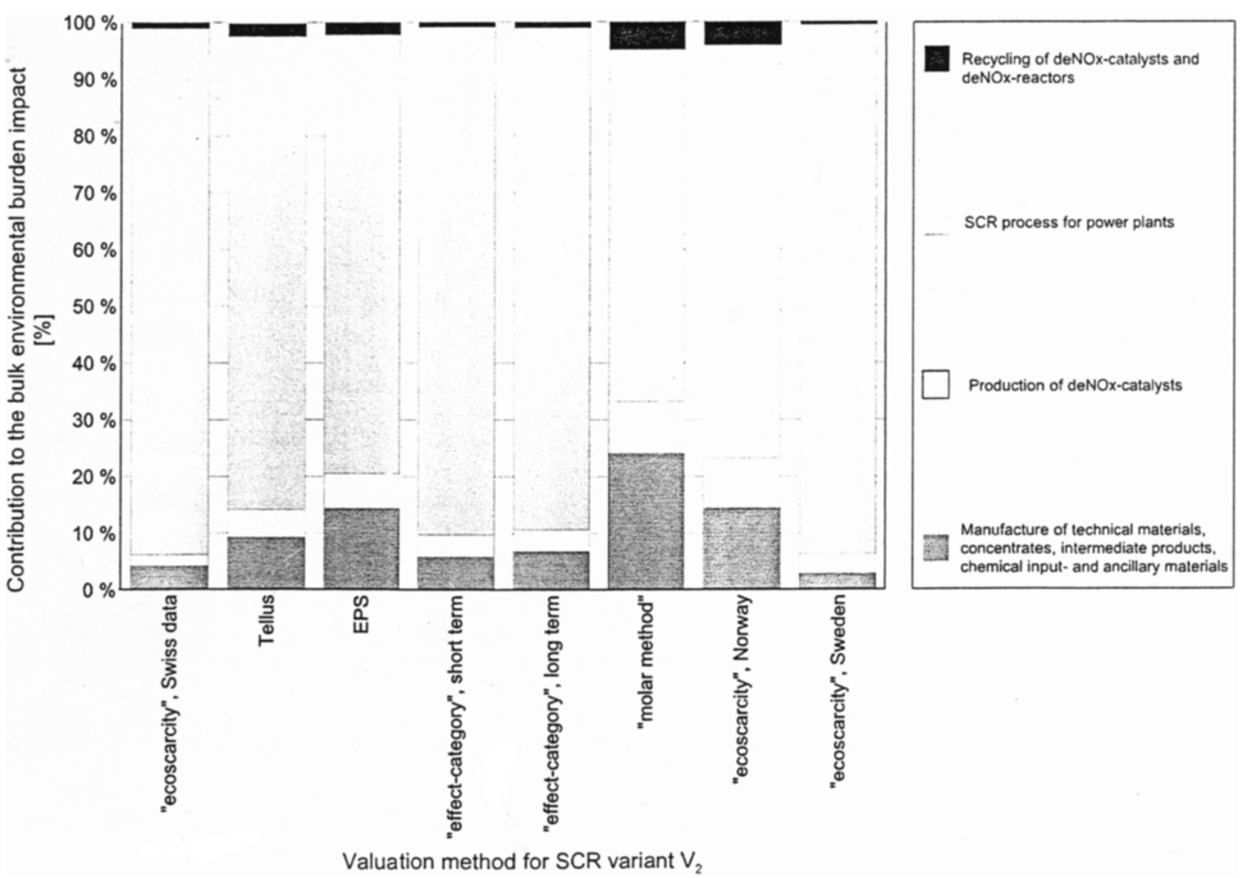

Fig. 6: Contribution from the PLC stages to the bulk environmental burden impact for the SCR variant V_2

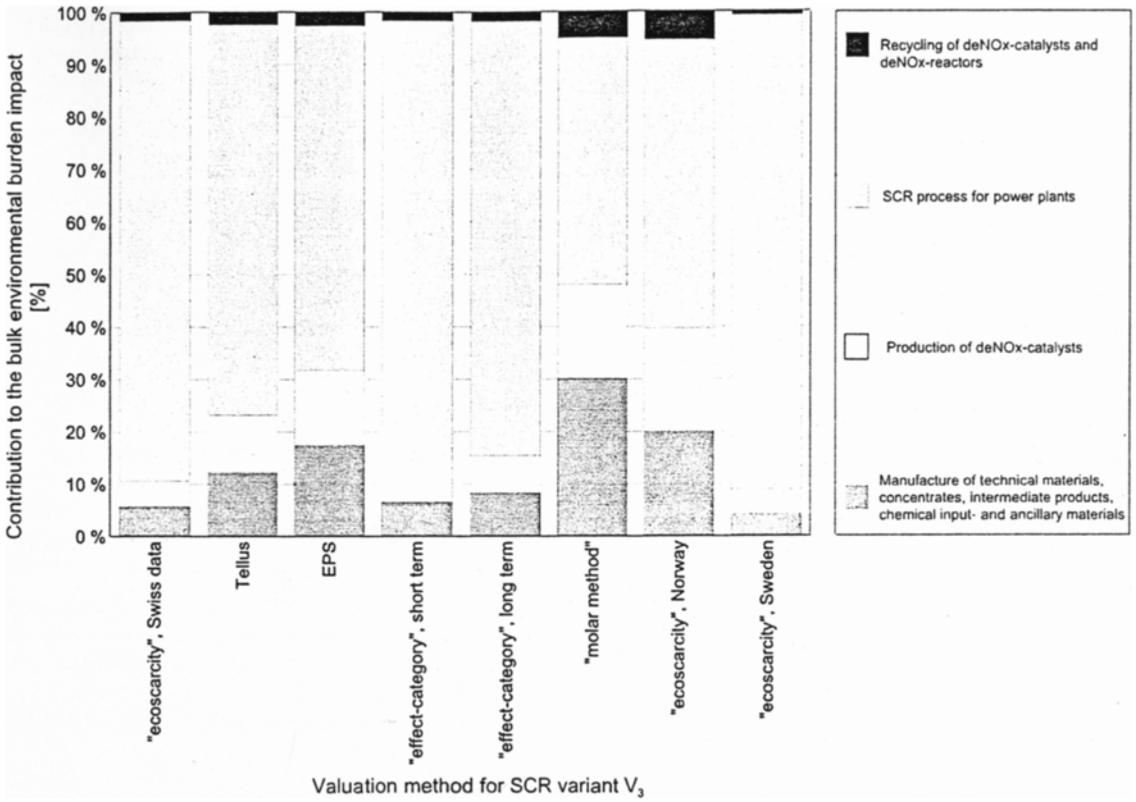

Fig. 7: Contribution from the PLC stages to the bulk environmental burden impact for the SCR variant V_3

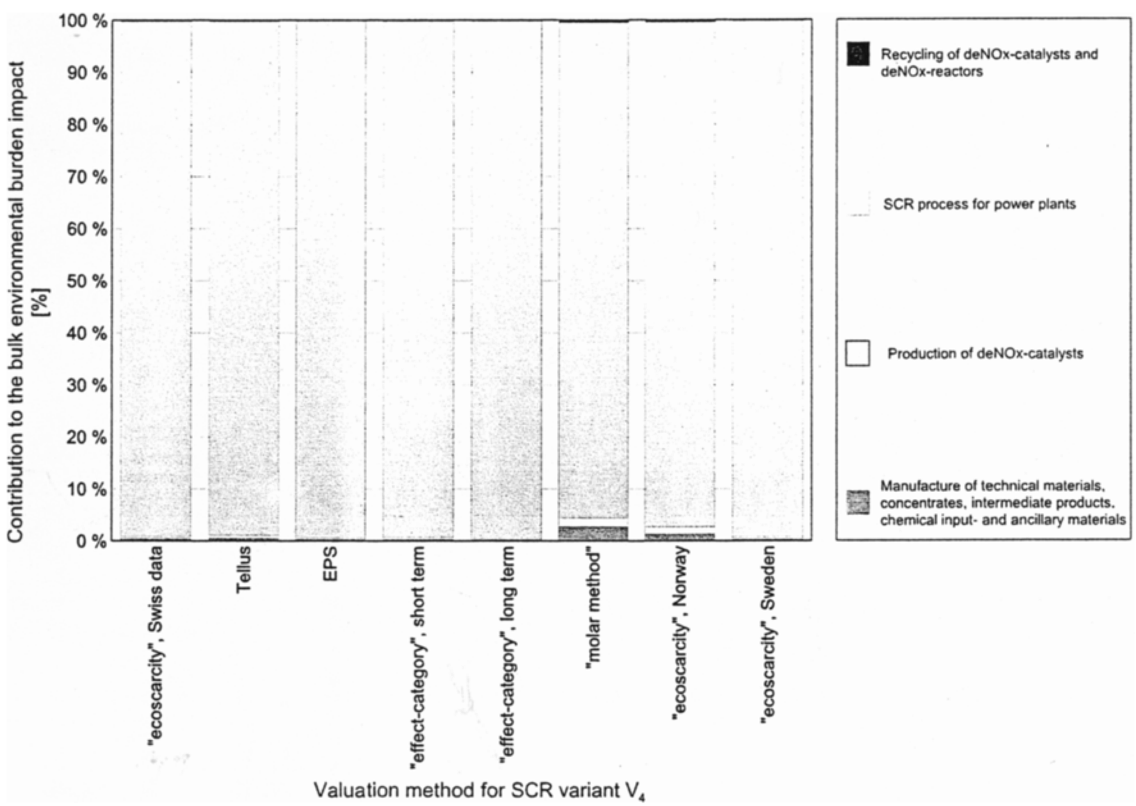

Fig. 8: Contribution from the PLC stages to the bulk environmental burden impact for the SCR variant V_4

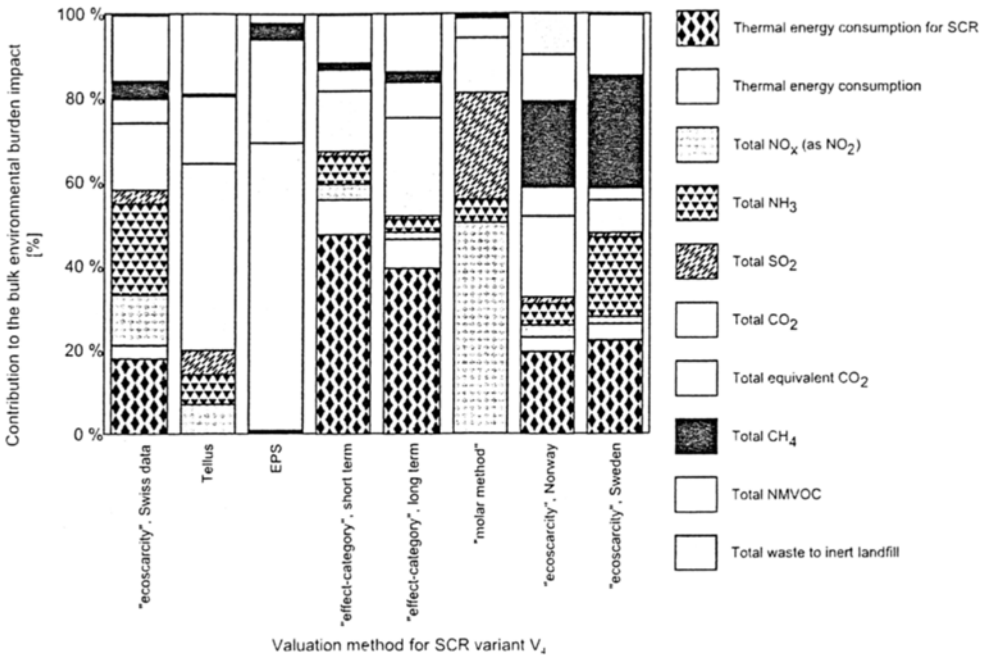

Fig. 9: Contribution from the environmental pollutants to the bulk environmental burden impact for the SCR variant V_4

4 Nomenclature

BB_j	Contribution to the Bulk environmental Burden impact from the in or output j
BBE_j	Bulk Burden on Environment of in or output of j
BR_j	Bulk ecological Relief of the bulk reduction of load on environment of the in or output of j
$BRLE_j$	Bulk Reduction of Load on Environment of the in or output of j
CQR	Concept of Quality target Relations ("molar method")
$deNO_x$	Denitrification
EE	Ecological Effectiveness
EI	Environmental Impact
ELU	Environmental Load Units
EPC	Environmental Protection Costs
EPS	Environmental Priority Strategies in product design
EPSU	Environmental Pollution Source Units
ERP	Ecological Relief Points
FGD	Flue Gas Desulfurization plant
HC	Hydrocarbons without methane
HW	Hazardous Waste
HWCP	Hazardous Waste Combustion Plant
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
NO_x	Nitrogen Oxides
P_{el}	Electric Power
PLC	Product Life Cycle
R	Overall ecological Relief of the LCIA
SCR	Selective Catalytic Reduction
tkm	ton-kilometer
V_1	High-dust system for slag tap firing (hard coal), 1,000 m^3 plate type 1
V_2	High-dust system for dry firing (hard coal), 1,000 m^3 plate type 2
V_3	High-dust system for dry firing (hard coal), 1,000 m^3 honeycomb
V_4	Low-dust system downstream of FGD (hard coal), 1,000 m^3 honeycomb
WCP	Waste Combustion Plant
η	Effectiveness of the process sequence for electric power supply in the Federal German interconnected power system

5 References

[1] KALMBACH, S.; SCHMÖLLING, J. (1990): Technische Anleitung zur Reinhaltung der Luft. 3., aktualisierte und erweiterte Auflage. Erich Schmidt, Berlin

[2] Siemens AG Power Generation (KWU) (1990): Stickoxidminderung mit Platten- und Wabenkatalysatoren. Siemens AG, Erlangen

[3] BÁRZAGA-CASTELLANOS, L.; NEUFERT, R.; KAYSER, G.; MARKERT, B. (1998): Ökobilanzierung des selektiven katalytischen Reduktionsverfahrens. Gefahrstoffe - Reinhaltung der Luft, 58, pp 313-319

[4] DIN (1997): Environmental management – Life cycle assessment – Principles and framework (German EN ISO 14040 and English ISO 14040 version). Beuth, Berlin

[5] DIN (1997): Environmental management – Life cycle assessment – Goal and scope definition and life cycle inventory analysis (German prEN ISO 14041 and English ISO/DIS 14041 version). Beuth, Berlin

[6] BRAUNSCHWEIG, A.; MÜLLER-WENK, R. (1993) Ökobilanzen für Unternehmungen - Eine Wegleitung für die Praxis. Paul Haupt, Bern, Stuttgart, Wien

[7] VDI (1995): Kumulierter Energieaufwand, Begriffe, Definitionen, Berechnungsmethoden. VDI 4600 Draft. Beuth, Berlin, Düsseldorf

[8] VIGON, B.W.; TOLLE, D.A.; CORNABY, B.W.; LATHAM, H.C.; HARRISON, C.L.; BOGUSKI T.L.; HUNT, R.G. (1994): Life-Cycle Assessment, Inventory Guidelines and Principles. Lewis Publishers, Boca Raton, FL, USA

[9] LINDFORS, L.G. et al. (1995): Nordic Guidelines on Life-Cycle Assessment. Nordic Council of Ministers, Copenhagen, Denmark

[10] BRAUNSCHWEIG, A.; FÖRSTER, R.; HOFSTETTER, P.; MÜLLER-WENK, R. (1994): Evaluation und Weiterentwicklung von Bewertungsmethoden für Ökobilanzen. Institut für Wirtschaft und Ökologie, St. Gallen, Schweiz

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Annex

Table 1: LCI of SCR for process sequence evaluation, each based on 2,000 m^3 of honeycomb or plate-type $deNO_x$ catalyst

Pollutant in kg	BRLE SCR Honeycomb	BBE SCR Honeycomb	BRLE SCR Plate	BBE SCR Plate
Transport in tkm:		34,297,309		21,738,740
Affected area in m^2:		93,413		73,028
Energy:				
Thermal energy consumption in GJ[a]		25,106,310		
Thermal energy consumption in GJ		5,146,477		1,242,177
Electrical energy consumption in MWh		24,210		13,719
Air pollution burden:				
Total NO_x (as NO_2)	283,820,684	420,704	105,541,081	30,886
Total NH_3		920,405		305,124
Total SO_2		229,442		34,574
Total CO_2		563,179,871		11,300,552
Equivalent CO_2		204,809,354		8,201,295
Total CO		2,802,415		112,654
Total CH_4		2,959,650		128,272
Total HC		1,595,802		66,385
Total ash		40,340		6,949
Total HCl		647		261
Water pollution burden:				
Total chloride		76,753		31,358
Total sulfates		881,146		341,130
NH_4 (total N)		238		97
Total greases and oils		1,820		718
Total iron		448,009		170,800
Total Na^+		400		334
Total waste:				
Recycling		840,629		1,352,676
Reprocessing		1,684,490		74,346
Inert landfill		3,326,969		751,697
Residue landfill		41,391		18,879
Reactor landfill		3,793		1,721
Municipal waste to WCP		39,366		28,892
HW to HWCP		9,026		10,105
HW to underground landfill		0		11,912
Land farming		14,677		5,859

[a] Thermal energy consumption for low-dust system downstream of FGD for reheating of the cold flue gases to the operating temperature for the $deNO_x$ reactor (→ V_4, Table 3)

Table 2: Input-data for the four application variants of deNOx catalyst in power plants

Parameter	V_1	V_2	V_3	V_4
Catalyst type	**Plate type 1**	**Plate type 2**	**Honeycomb**	**Honeycomb**
Exhaust flow (in standard condition, humid) in m^3/h	600,000	600,000	600,000	600,000
SCR temperature in °C	350	350	350	300
NO_x SCR inlet (as NO_2, in standard condition, dry, reference O_2) in mg/m^3	1,000	800	800	800
NO_x SCR outlet (as NO_2, in standard condition, dry, reference O_2) in mg/m^3	200	200	200	200
NO_x reduction rate in %	80	75	75	75
NO_x reduction in kg NO_x/1000 h operating time	447,000	357,600	357,600	357,600
Humidity (volume % H_2O, absolutely)	10	10	10	10
NH_3 slip in mg/m^3 (end of catalyst service life, in standard condition, dry, reference O_2)	3.86	3.86	3.86	3.86
Catalyst operating period in h	14,000	16,000	16,000	24,000
Catalyst volume in m^3 (1st load)	233	207	164	81.2
Occupied layers	3	2	2	2
Free layers	1	1	1	1
Steel used for 1 $deNO_x$ reactor in t	180	180	180	180
Catalyst revenue load in h	14,000	16,000	16,000	24,000
Catalyst change in h	37,000 1st layer	40,000 1st layer	40,000 1st layer	76,000 50% of 1st load
	47,000 2nd layer	56,000 2nd layer	56,000 2nd layer	105,000 50% of 1st load
	59,600 3rd layer			

Table 3: Input-output process balance and absolute NO_x reduction costs of SCR (calculated with 1.00 U.S.$ = 1.80 DM) for four application variants [3]

Parameter	V_1	V_2	V_3	V_4
Catalyst type	Plate type 1	Plate type 2	Honeycomb	Honeycomb
NO_x reduction rate in %	80	75	75	75
Total catalyst volume in m^3	1,000	1,000	1,000	1,000
Total catalyst run time in h	127,897	135,266	170,731	622,951
NO_x reduction in t	57,170	48,371	61,053	222,767
NH_3 use in t	20,248	17,131	21,623	78,897
NH_3 slip in t	148	157	198	721
Energy use (natural gas) in TJ	-	-	-	25,106
CO_2 emissions (energy use) in t	-	-	-	444,787
Number of deNO_x reactors	1	1	1	3[1]
Steel used in t	180	180	180	540
Absol. NO_x reduction costs in 10^6 U.S.$	71.46	101.85	128.55	749.98

Observation from Table 3:
[1] Number of deNO_x reactors is a theoretical value, based on a comparable total service time of the fixed total catalyst volume (only for calculation).

Table 4: Specific cumulated energy demand for manufacturing of deNO_x catalysts (all data is based on the process sequences investigated in this report with the associated boundaries and restrictions)

Specific cumulated energy demand	DeNO_x catalyst manufacturing process	
	Honeycomb-type catalyst	**Plate-type catalyst**
Thermal energy	54.3 in GJ/t catalyst	41.0 in GJ/t catalyst
Electrical energy	5.9 in MWh/t catalyst	6.8 in MWh/t catalyst
Total at η = 0.38	110.3 in GJ/t catalyst	105.4 in GJ/t catalyst

Table 5: Specific cumulated energy demand for overall SCR process cycle (all data is based on the process sequence investigated in this report with the associated boundaries and restrictions)

Specific cumulated energy demand	SCR process sequence investigated	
	Honeycomb-type catalyst	**Plate-type catalyst**
Thermal energy	106.6 in MJ/kg NO_x	11.8 in MJ/kg NO_x
Electrical energy	85.3 in Wh/kg NO_x	130.0 in Wh/kg NO_x
Total at η = 0.38	107.4 in MJ/kg NO_x	13.0 in MJ/kg NO_x

Table 6: Overall ecological relief of the ecologicaal PLC for four SCR variants employing two different deNO_x catalyst types, each with 1,000 m^3 of catalyst

Valuation method	V_1 in 10^6	V_2 in 10^6	V_3 in 10^6	V_4 in 10^6
ecoscarcity, Swiss data in ERP	2,390,625	2,022,372	2,552,003	9,216,038
Tellus U.S.A., in reduction of U.S.$ costs	455.65	385.36	486.17	1,734.22
EPS, in reduction of ELU (approx. 1 ECU)	11.31	9.54	11.84	-24.41
effect-category, in reduction of short term goals	223,813	189,244	238,740	836,226
effect-category, in reduction of long term goals	223,107	188,648	237,903	791,937
CQR ("molar method"), in reduction of EPSU	305,011	258,052	325,618	1,185,146
ecoscarcity, Norwegian data in ERP	518,612	438,597	551,513	1,915,609
ecoscarcity, Swedish data in ERP	263,746	222,517	280,622	942,600

Table 7: Ecological effectiveness of the ecological PLC for four SCR variants employing two different deNO_x catalyst types, each with 1,000 m^3 of catalyst

Valuation method	V_1	V_2	V_3	V_4
ecoscarcity, Swiss data in ERP/U.S.$	33,453	19,857	19,852	12,288
Tellus U.S.A., in reduction of U.S.$ costs/U.S.$	6.38	3.78	3.78	2.31
EPS, in reduction of ECU costs/U.S.$	0.16	0.09	0.09	-0.03
effect-category, in reduction of short term goals/U.S.$	3,132	1,858	1,857	1,115
effect-category, in reduction of long term goals/U.S.$	3,122	1,852	1,851	1,056
CQR ("molar method"), in reduction of EPSU /U.S.$	4,268	2,534	2,533	1,580
ecoscarcity, Norwegian in ERP/U.S.$	7,257	4,306	4,290	2,554
ecoscarcity, Swedish data in ERP/U.S.$	3,691	2,185	2,183	1,257